Constraining Two Higgs doublet Models

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Probing the SM and NP at Low and High Energies

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on-going collaboration with

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Two Higgs doublet models (2HDM)

Several Motivations

- New sources of CP violation

  SM cannot account for BAU

- Possibility of having spontaneous CP violation

  EW sym breaking and $\cancel{CP}$ same footing

  T. D. Lee 1973 ; Kobayashi and Maskawa 1973

- Strong CP problem , Peccei-Quinn

- Supersymmetry

LHC important rôle

Neutral currents have played an important rôle in the construction and experimental tests of unified gauge theories

EPS Prize in 2009 to Gargamelle, CERN

In the Standard Model Flavour Changing Neutral Currents (FCNC) are forbidden at tree level

- in the gauge sector, ie no Z FCNC
- in the scalar sector, ie no HFCNC

Models with two or more Higgs doublets potentially large HFCNC

strict limits on FCNC processes!

Proposed solutions, case of Multi-Higgs models

without HFCNC

NFC — Weinberg, Glashow (1977)
Paschos (1977)

Aligned two-Higgs-doublet model
Pich, Tuzon (2009)

with HFCNC

existence of suppression factors in HFCNC
Antaramian, Hall, Rasin (1992)
Hall, Weinberg (1993)
Joshipura, Rindani (1991)

- first models of this type with no ad-hoc assumption
suppression by small elements of V_{CKM} : BGL models
Branco, Grimus, Lavoura (1996)

Minimal Flavour Violation

Notation

Yukawa interactions

$$\mathcal{L}_Y = -\overline{Q_L^0}\,\Gamma_1\,\Phi_1\,d_R^0 - \overline{Q_L^0}\,\Gamma_2\,\Phi_2\,d_R^0 - \overline{Q_L^0}\,\Delta_1\,\tilde{\Phi}_1\,u_R^0 - \overline{Q_L^0}\,\Delta_2\,\tilde{\Phi}_2\,u_R^0 + h.c.$$

$$\tilde{\Phi}_i = -i\tau_2\,\Phi_i^*$$

Quark mass matrices

$$M_d = \frac{1}{\sqrt{2}}\left(v_1\Gamma_1 + v_2 e^{i\alpha}\Gamma_2\right) ; \quad M_u = \frac{1}{\sqrt{2}}\left(v_1\Delta_1 + v_2 e^{-i\alpha}\Delta_2\right)$$

Diagonalized by

$$U_{d_L}^\dagger\, M_d\, U_{dR} = D_d \equiv \mathrm{diag}\,(m_d, m_s, m_b)$$

$$U_{u_L}^\dagger\, M_u\, U_{uR} = D_u \equiv \mathrm{diag}\,(m_u, m_c, m_t)$$

Leptonic Sector

$$-\overline{L_L^0}\,\Pi_1\,\Phi_1\,\ell_R^0 - \overline{L_L^0}\,\Pi_2\,\Phi_2\,\ell_R^0 + h.c.$$

$$\left(-\overline{L_L^0}\,\Sigma_1\,\tilde{\Phi}_1\,\nu_R^0 - \overline{L_L^0}\,\Sigma_2\,\tilde{\Phi}_2\,\nu_R^0 + h.c\right)$$

$$\left(\frac{1}{2}\,\nu_R^{0\,T}\,C^{-1}\,M_R\,\nu_R^0 + h.c\right)$$

Expansion around the vev's

$$\phi_j = \begin{pmatrix} \phi_j^+ \\ \frac{e^{i\alpha_j}}{\sqrt{2}} (v_j + \rho_j + i\eta_j) \end{pmatrix}, \quad j = 1,2$$

we perform the following transformation

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = U \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} ; \quad \begin{pmatrix} G^0 \\ I \end{pmatrix} = U \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} ; \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$U = \frac{1}{v} \begin{pmatrix} v_1 e^{-i\alpha_1} & v_2 e^{-i\alpha_2} \\ v_2 e^{-i\alpha_1} & -v_1 e^{-i\alpha_2} \end{pmatrix} ; \quad v = \sqrt{v_1^2 + v_2^2} = \left(\sqrt{2}\, G_F\right)^{-1/2} \simeq 246\,\text{GeV}$$

U singles out

H^0 with couplings to quarks proportional to mass matrices

G^0 neutral pseudo-Goldstone boson

G^+ charged pseudo-Goldstone boson

Physical neutral Higgs fields are combinations of H^0, R and I

Neutral and charged Higgs interactions for the quark sector

$$\mathcal{L}_Y(\text{quark, Higgs}) = -\overline{d_L^0}\,\frac{1}{v}\left(M_d H^0 + N_d^0 R + i N_d^0 I\right) d_R^0 +$$

$$+\,\overline{u_L^0}\,\frac{1}{v}\left[M_u H^0 + N_u^0 R + i N_u^0 I\right) u_R^0 +$$

$$+\,\frac{\sqrt{2}H^+}{v}\left(\overline{u_L^0}\, N_d^0\, d_R^0 - \overline{u_R^0}\, N_u^{0\dagger}\, d_L^0\right) + h.c.$$

$$N_d^0 = \frac{1}{\sqrt{2}}\left(v_2 \Gamma_1 - v_1 e^{i\alpha}\Gamma_2\right), \quad N_u^0 = \frac{1}{\sqrt{2}}\left(v_2 \Delta_1 - v_1 e^{-i\alpha}\Delta_2\right)$$

Flavour structure of quark sector of 2HDM characterized by

M_d, M_u, N_d^0, N_u^0

likewise leptonic sector, Dirac neutrinos

M_ℓ, M_ν, N_ℓ^0, N_ν^0

Yukawa couplings in terms of quark mass eigenstates for H^+, H^0, R, I

$$\mathcal{L}_Y = \dots \sqrt{2}\,\frac{H^+}{v}\,\bar{u}\left(-V N_d \gamma_R + N_u^\dagger V \gamma_L\right) d + h.c. -$$

$$- \frac{H^0}{v}\left(\bar{u} D_u u + \bar{d} D_d d\right) -$$

$$- \frac{R}{v}\left[\bar{u}\left(N_u \gamma_R + N_u^\dagger \gamma_L\right) u + \bar{d}\left(N_d \gamma_R + N_d^\dagger \gamma_L\right) d\right] +$$

$$+ i\,\frac{I}{v}\left[\bar{u}\left(N_u \gamma_R - N_u^\dagger \gamma_L\right) u - \bar{d}\left(N_d \gamma_R - N_d^\dagger \gamma_L\right) d\right]$$

$$\gamma_L = (1-\gamma_5)/2\,;\quad \gamma_R = (1+\gamma_5)/2 \qquad V \equiv V_{CKM}$$

Flavour changing neutral currents controlled by:

$$N_d = \frac{1}{\sqrt{2}} U_{d_L}^{\dagger} \left(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2 \right) U_{d_R}$$

$$N_u = \frac{1}{\sqrt{2}} U_{u_L}^{\dagger} \left(v_2 \Delta_1 - v_1 e^{-i\alpha} \Delta_2 \right) U_{u_R}$$

For generic two Higgs doublet models N_u, N_d non-diagonal arbitrary

For definiteness rewrite N_d :

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{d_L}^{\dagger} e^{i\alpha} \Gamma_2 U_{d_R}$$

conserves flavour

leads to FCNC

The flavour structure of Yukawa couplings is not constrained by gauge invariance

All flavour changing transition in SM are mediated by charged weak currents with flavour mixing controlled by V_{CKM}

MFV essentially requires flavour and CP violation linked to known structures of Yukawa couplings

[all new flavour changing transitions are controlled by the CKM matrix]

About Minimal Flavour Violation

Buras, Gambino, Gorbahn, Jager, Silvestrini (2001)
D'Ambrosio, Giudice, Isidori, Strumia (2002)

leptonic sector

Cirigliano, Grinstein, Isidori, Wise (2005)

$G_F = U(3)^5$ largest symmetry of the gauge sector
flavour violation completely determined by Yukawa couplings

Our framework
- multi-Higgs models
- no Natural Flavour Conservation
- must obey above condition (one of the defining ingredients of MFV framework)

In order to obtain a structure for Γ_i, Δ_i such that FCNC at tree level strength completely controlled V_{CKM}

Branco, Grimus, Lavoura imposed symmetry

$$Q^0_{L_j} \to \exp(i\tau) Q^0_{L_j} \; ; \quad u^0_{R_j} \to \exp(2i\tau) u^0_{R_j} \; ; \quad \Phi_2 \to \exp(i\tau) \Phi_2 \, , \quad \tau \neq 0, \pi$$

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} ; \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix} ; \quad \Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} ; \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$j = 3$$

Both Higgs have non-zero Yukawa couplings in the up and down secto

Special WB chosen by the symmetry

FCNC in down sector

if instead of $u^0_{R_j} \to \exp(2i\tau) u^0_{R_j}$ impose $d^0_{R_j} \to \exp(2i\tau) d^0_{R_j}$

then FCNC in up sector

Six different BGL models

$$(N_d)_{rs} = \frac{v_2}{v_1}(D_d)_{rs} - \left(\frac{v_2}{v_1}+\frac{v_1}{v_2}\right)\underbrace{(V^{\dagger}_{CKM})_{r3}(V_{CKM})_{3s}}_{\text{MFV}}(D_d)_{sp}$$

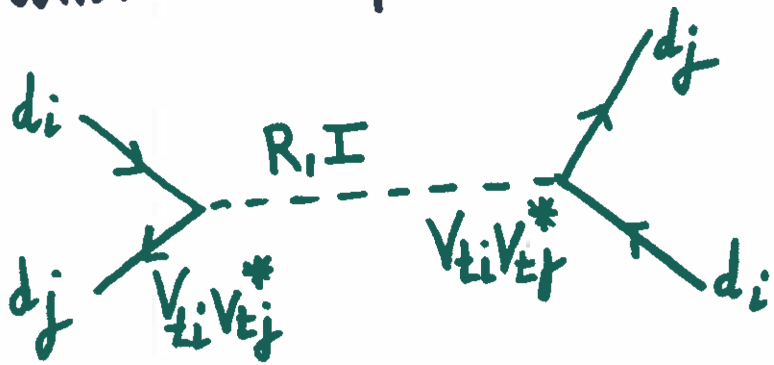
$j = 3$

$$N_u = -\frac{v_1}{v_2}\,\mathrm{diag}(0,0,m_t) + \frac{v_2}{v_1}\,\mathrm{diag}(m_u, m_c, 0)$$

FCNC only in the down sector
suppression by the 3rd row of V_{CKM}
dependence on V_{CKM} and $\tan\beta$ only

Strong and Natural suppression of the most constrained processes

e.g. $|V_{td}V_{ts}^*|^2 \sim \lambda^{10}$



What is the necessary condition for N_d^0, N_u^0 to be of MFV type?

Should be functions of M_d, M_u no other flavour dependence

Furthermore, N_d^0, N_u^0 should transform appropriately under WB

$$Q_L^0 \to W_L Q_L^0 \,, \quad d_R^0 \to W_R^d d_R^0 \,, \quad u_R^0 \to W_R^u u_R^0$$

$$M_d \to W_L^\dagger M_d W_R^d \,, \quad M_u \to W_L^\dagger M_u W_R^u$$

N_d^0, N_u^0 transform as M_d, M_u

$$N_d^0 \propto M_d \;;\; (M_d M_d^\dagger) M_d \;;\; (M_u M_u^\dagger) M_d$$

$$Y_d \;;\; (Y_d Y_d^\dagger) Y_d \;;\; (Y_u Y_u^\dagger) Y_d \quad \text{Yukawa}$$

see previous references

What is particular about BGL models in MFV context?

$$M_d M_d^\dagger \equiv H_d \; ; \quad U_{d_L}^\dagger M_d U_{d_R} = D_d \; ; \quad U_{d_L}^\dagger H_d U_{d_L} = D_d^2$$

$$D_d^2 = \mathrm{diag}(m_d^2, m_s^2, m_b^2) = m_d^2 \underbrace{\begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}}_{P_1} + m_s^2 \underbrace{\begin{pmatrix} 0 & & \\ & 1 & \\ & & 0 \end{pmatrix}}_{P_2} + m_b^2 \underbrace{\begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix}}_{P_3}$$

$$D_d^2 = \sum_i m_{d_i}^2 P_i$$

$$H_d = U_{d_L} D_d^2 U_{d_L}^\dagger = \sum_i m_{d_i}^2 U_{d_L} P_i U_{d_L}^\dagger = \sum_i m_{d_i}^2 P_i^{d_L}$$

$U_{d_L} P_i U_{d_L}^\dagger$ rather than $Y_d Y_d^\dagger$ are the minimal building blocks to be used in the expansion of N_d^0, N_u^0 conforming to the MFV requirement

Botella, Nebot, Vives 2004

It is convenient to write H_d, H_u in terms of projection operators

Botella, Nebot, Vives 2004

$$H_d = \sum_i m_{d_i}^2 P_i^{dL} \; ; \quad P_i^{dL} = U_{dL} P_i U_{dL}^\dagger \; ; \quad (P_i)_{jk} = \delta_{ij}\delta_{ik} \qquad u \leftrightarrow d$$

MFV expansion for N_d^0 and N_u^0

$$N_d^0 = \lambda_1 M_d + \lambda_{2i} U_{dL} P_i U_{dL}^\dagger M_d + \lambda_{3i} U_{uL} P_i U_{uL}^\dagger M_d + \dots$$

$$N_u^0 = \tau_1 M_u + \tau_{2i} U_{uL} P_i U_{uL}^\dagger M_u + \tau_{3i} U_{dL} P_i U_{dL}^\dagger M_u + \dots$$

In green terms that do not lead to FCNC

In red terms that lead to FCNC

In the quark eigenstate basis

$$N_d = \lambda_1 D_d + \lambda_{2i} P_i D_d + \lambda_{3i} (V_{CKM})^\dagger P_i V_{CKM} D_d + \dots$$

$$N_u = \tau_1 D_u + \tau_{2i} P_i D_u + \tau_{3i} V_{CKM} P_i (V_{CKM})^\dagger D_u + \dots$$

At this stage λ and τ coefficients appear as free parameters, MFV

Need for additional symmetries in order to constrain these coeff.

WB covariant definition for BGL models

$$N_d^0 = \frac{v_2}{v_1} M_d - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) \mathcal{P}_j^\gamma M_d$$

$$N_u^0 = \frac{v_2}{v_1} M_u - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) \mathcal{P}_j^\gamma M_u$$

together with

$$\mathcal{P}_j^\gamma \Gamma_2 = \Gamma_2 \quad , \quad \mathcal{P}_j^\gamma \Gamma_1 = 0$$

$$\mathcal{P}_j^\gamma \Delta_2 = \Delta_2 \quad , \quad \mathcal{P}_j^\gamma \Delta_1 = 0$$

γ stands for u (up) or d (down)

$\mathcal{P}_j^\gamma$ are projection operators   Botella, Nebot, Vives 2004

$$\mathcal{P}_j^u = U_{uL} P_j U_{uL}^\dagger \qquad \mathcal{P}_j^d = U_{dL} P_j U_{dL}^\dagger$$

$$(P_j)_{\ell k} = \delta_{j\ell} \delta_{jk}$$

e.g. $P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

BGL is the only implementation of models where Higgs FCNC are a function of V_{CKM} only (together with v_1, v_2) which are based on an Abelian symmetry obeying the sufficient conditions of having M_u block diagonal together with the existence of a matrix P such that

$$P\Gamma_2 = \Gamma_2 \quad ; \quad P\Gamma_1 = 0$$

Ferreira, Silva arXiv: 1012287

Flavour structure (quark sector)

M_d, M_u, N_d^0, N_u^0

Freedom of choice of WB

Zero textures are WB dependent

Symmetries are only apparent in particular WB

WB transformations do not change the physics

Symmetries have physical implications

Above four matrices encode breaking of flavour symmetry present in gauge sector

large redundancy of parameters

WB invariants are very useful to study flavour

see previous talk by G.C. Branco

The leptonic sector

Required for completeness

- study of experimental implications
- study of stability under RGE

Models with two Higgs doublets with FCNC

- controlled by V_{CKM} in the quark sector
- controlled by V_{PMNS} in the leptonic sector

Case of Dirac neutrinos, straightforward

Same flavour structure

Six different BGL-type models

Scalar Potential

the softly broken Z_2 symmetric 2HDM potential

$$V(\Phi_1,\Phi_2) = m_{11}^2\,\phi_1^\dagger\phi_1 + m_{22}^2\,\phi_2^\dagger\phi_2 - \left(m_{12}^2\,\phi_1^\dagger\phi_2 + h.c.\right) + \frac{1}{2}\lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\phi_2^\dagger\phi_2\right)^2$$

$$+\lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \frac{1}{2}\left[\lambda_5\left(\phi_1^\dagger\phi_2\right)^2 + h.c.\right]$$

$$\phi_1 \to \phi_1 \;,\; \phi_2 \to -\phi_2$$

in our case $\phi_1 \to \phi_1$, $\phi_2 \to e^{iz}\,\phi_2$, $z \neq 0, \pi$ no λ_5 term

V does not violate CP neither explicitly nor spontaneously

7 free parameters : m_h, m_H, m_A, $m_{H^\pm}$, $v=\sqrt{v_1^2+v_2^2}$, $\tan\beta$, α (H^0, R)

soft symmetry breaking prevents ungauged accidental continuous symmetry

Analysis of implications, 36 BGL models

Experimental constraints

- Neutral Meson Mixing
- Leptonic decays of pseudoscalar mesons $P^+ \to \ell^+ \nu_\ell$
- Charged Lepton Decays
- $B \to \tau \nu$, $B \to D \tau \nu$, $B \to D^* \tau \nu$
- Oblique parameters and Direct Searches for $H^\pm$
- $Z \to b\bar{b}$
- $b \to s\gamma$
- $\ell_j \to \ell_i \gamma$: $\tau \to \mu\gamma$, $\mu \to e\gamma$

$Z \to b\bar{b}$ strongest constraint

Best BGL implementation HFCNC up quark sector $j=3$
HFCNC ν sector $j=3$

reasonable values $\tan\beta$ versus $M_{H^\pm}$ relaxing $Z \to b\bar{b}$

Relaxing T parameter, there are other BGL type models that become interesting

Models with NFC

single scalar doublet coupling to each type of f_R

The softly broken Z_2 symmetric 2HDM potential

CP conserving type I and type II

recent work Barroso, Ferreira, Haber, Ivanov, Santos, Sher, Silva

2HDM type II Yukawa with CP violation

Basso, Lipniacka, Mahmoudi, Moretti, Osland, Pruna, Purmohammadi (2012)

Conclusions

LHC results may bring surprises for the Higgs sector, e.g. discovery of charged Higgs

There are new mechanisms beyond NFC to obtain strong suppression of FCNC as required by experiment

BGL-type models are very interesting candidates for New Physics

The softly broken Z_2 symmetric 2HDM potential

$$\boxed{\begin{aligned} V(\Phi_1,\Phi_2) &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}] \end{aligned}}$$

$$\boxed{\phi_1 \to \phi_1 \quad \phi_2 \to -\phi_2}$$

Build your favourite potential: <u>CP conserving</u>, <u>explicit CP breaking</u>, <u>spontaneous CP breaking</u>, by tuning m^2_{12} and λ_5 together with the possible vacuum configurations

- m^2_{12} and λ_5 real, vacuum configuration (CP-conserving)

$$\boxed{\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}}$$

7 free parameters + M_W: $m_h,\ m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \alpha,\ M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$

$\boxed{\tan\beta = \frac{v_2}{v_1}}$ ratio of vacuum expectation values

RUI SANTOS, MORIOND 2013

2HDM Lagrangian

- scalars-gauge bosons couplings

$$\boxed{g_{SM}\sin(\beta-\alpha)} \quad hW^+W^-$$

- Yukawa couplings

Extending the Z_2 symmetry to the fermions - 4 independent Yukawa Lagrangians

$$\boxed{g_{SM}\frac{f(\alpha)}{g(\beta)}} \quad h\bar{f}f$$

	I	II	III	IV
up	Φ_2	Φ_2	Φ_2	Φ_2
down	Φ_2	Φ_1	Φ_1	Φ_2
lepton	Φ_2	Φ_1	Φ_2	Φ_1

III = I' = Y = Flipped

IV = II' = X = Leptonic

we use as independent parameters

$$\boxed{\sin\alpha \quad \tan\beta}$$

	I	II	III	IV
leptons (h)	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
down (h)	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$
up (h)	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
leptons (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
down (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$
up (H)	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$

THE CONSTRAINTS

EXP

$B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$ mixing

$R_b \equiv \Gamma(Z \to b\bar{b}) / \Gamma(Z \to \text{hadrons})$

Precision electroweak constraints

$B^+ \to \tau^+ \nu_\tau$

LEP from $e^+e^- \to H^+H^-$ $\qquad m_{H^\pm} \gtrsim 94\ \text{GeV}$

B factories from $B \to X_s \gamma$ $\qquad m_{H^\pm} \gtrsim 360\ \text{GeV}$ (Type II)

ATLAS, CMS $\qquad pp \to t\bar{t} \to \bar{b}b W^+ H^-$ $\qquad m_{H^+}$ versus $\tan\beta$

THEO

POTENTIAL BOUNDED FROM BELOW

UNITARITY LIMITS for QUARTIC Higgs couplings

NORMAL GLOBAL MINIMUM, unique

LHC data

- Set m_h = 125 GeV.

- Generate random values for potential's parameters such that

$$90\ Gev \leqslant m_{H^\pm},\ m_A \leqslant 900\ GeV$$

$$m_h \leqslant m_H \leqslant 900\ GeV$$

$$1 \leqslant \tan\beta \leqslant 40$$

$$-\frac{\pi}{2} \leqslant \alpha \leqslant \frac{\pi}{2}$$

$$-(900)^2\ Gev^2 \leqslant m_{12}^2 \leqslant 900^2\ GeV^2$$

- Impose all experimental and theoretical constraints previously described.

- Calculate all branching ratios and production rates at the LHC.

- Impose averaged ATLAS and CMS results:

Arbey, Battaglia, Djouadi, Mahmoudi, 1211.4004.

$$\mu_{\gamma\gamma} = 1.66 \pm 0.33$$

$$\mu_{ZZ} = 0.93 \pm 0.28$$

$$\mu_{\tau\tau} = 0.71 \pm 0.42$$

$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

CP-conserving 2HDM with
lighest CP-even Higgs 125 GeV
is being severely cornered into
SM-like limit

2HDM notation 1

$$V = \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$
$$- \frac{1}{2}\left\{m_{11}^2(\Phi_1^\dagger\Phi_1) + \left[m_{12}^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] + m_{22}^2(\Phi_2^\dagger\Phi_2)\right\}$$

No FCNC:

$$\lambda_6 = 0; \quad \lambda_7 = 0$$

Allow CPV: $\lambda_5, \quad m_{12}^2$ complex

Constraints-experiment

- $b \to s\gamma$
- $\Gamma(Z \to b\bar{b})$
- $B \to \tau\nu(X)$, $B \to D\tau\nu$, $D \to \tau\nu$
- $B_0 \leftrightarrow \bar{B}_0$
- $B_{d,s} \to \mu^+\mu^-$
- EW constraints: S, T
- Electron EDM
- LHC: $H_1 \to \gamma\gamma$
- LHC: $H_{2,3} \to W^+W^-$

Constraints-theory

- Positivity
  - Explicit conditions
- Unitarity
  - Explicit conditions
- Perturbativity
- Global minimum
  - Three coupled cubic equations

Parameters

Input: $\boxed{\tan\beta,\ (M_1,\ M_2),\ (M_{H\pm},\ \mu^2),\ (\alpha_1,\ \alpha_2,\ \alpha_3)}$

Typically: step — fix — step — scan

$\mu^2 = \mathrm{Re}\, m_{12}^2 / 2\cos\beta\sin\beta$

$\sqrt{v_1^2 + v_2^2}$

Conclusions

- 2HDM II parameter space is severely constrained by LHC data
- Parts of 2HDM II parameter space are still open
- SM would be excluded by charged Higgs discovery
- $pp \to \underbrace{jj}_{W}\underbrace{\ell^\pm\nu}_{W}\underbrace{b\bar{b}}_{H_1}$ channel allows detection in part of parameter space

$pp \to H^\pm W^\mp \to W^+W^- b\bar{b}$

PER OSLAND
CORFU 2012